Efficiency and Capacity of a Bubble-Plate Fractionating Column

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Efficiency and Capacity of a Bubble-Plate Fractionating Column

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Experimental data are presented on the distillation of mixtures of ethyl alcohol and water in an 18-inch diameter, three-plate fractionating column. Data are given for plate spacings of 6, 12, and 18 inches, and for depths of liquid above the top of the slots of 0, 0.5, 1, and 2 inches over a range of velocities extending beyond the safe operating range.

Plate efficiencies as high as 120 per cent result from the concentration gradient across the plate. The entrainment occurring during distillation is measured colorimetrically.

For plate spacings of 6 and 12 inches the reduction in efficiency, as the velocity is increased, can be satisfactorily calculated on the basis of the quantity of entrainment. For a plate spacing of 18 inches the efficiency, as calculated from the quantity of entrainment, is too high.

A plot for evaluating the maximum allowable vapor rate for various values of the liquid seal and plate spacing is given. It is more economical to build a column of high plate spacing and small diameter than one of low plate spacing and large diameter.

A NUMBER of laboratory investigations of the plate efficiency of bubble-plate fractionating columns have been made in the past, but most of them have been primarily of a theoretical nature. Although a great deal of valuable information has been presented, all of these investigations are open to two criticisms from a practical viewpoint.

First, there is some question as to the applicability to large-scale equipment of efficiency data obtained from small bubble plates containing only one or two bubble caps. Second, in none of the laboratory investigations of plate efficiency have the experimental distilling columns been equipped with sufficient heating or condensing surface to run the columns to high vapor velocities.

As a result there is very little quantitative information in the literature as to allowable rates to which a distilling column may be run, nor are there any data to show what happens when various recommended velocities are exceeded.

Peters (*8*) was the first to report any values for the allowable rate to which a column may be run without priming. For two bubble-cap columns he reported the allowable vapor rate as 1.3 feet per second. For sieve plate columns running weak alcohol-water or acetic acid–water mixtures he gave the allowable vapor rate as 3 feet per second. He did not give sufficient data as to the mechanical designs to show what might have limited the capacity of the columns.

Souders and Brown (*11*) presented a graph for estimating the maximum allowable vapor velocity that can be used in commercial petroleum columns to obtain "satisfactory products." Their curves are based upon a few data from commercial columns. These data probably could not be used for systems other than petroleum mixtures in view of the fact that the requirements of "satisfactory products" from a petroleum column are quite different from those of other mixtures.

Garey, Griswold, Lewis, and McAdams (*1*) reported experimental data on three different laboratory columns, each with one cap per plate. They found the efficiency to be substantially constant over the range of 0.2 to 2.5 feet per second vapor velocity. What happened above 2.5 feet per second was not shown since the capacity of their columns was limited, in one case by the downpipes and in another by lack of heating surface.

Holbrook and Baker (*5*) reported data on an 8-inch, three-plate column containing two caps per plate with vapor velocities up to 6 feet per second. However, their investigation was confined to the determination of the entrainment for the system steam-water.

In recent years the importance of entrainment as a factor in determining the allowable vapor velocity through a column has come to be more fully recognized. Liquid drops carried by the vapor from one plate to the next above cut down the enrichment obtained and thus may limit the rate at which a column can be run.

Sherwood and Jenny (*10*) pointed out that the efficiency is not materially reduced by entrainment until an entrainment of about 10 per cent is reached. Rather high vapor rates are required to cause 10 per cent entrainment; these considerably alter the mechanism of vapor-liquid contact and may thus result in lowering the efficiency over and above that resulting from entrainment.

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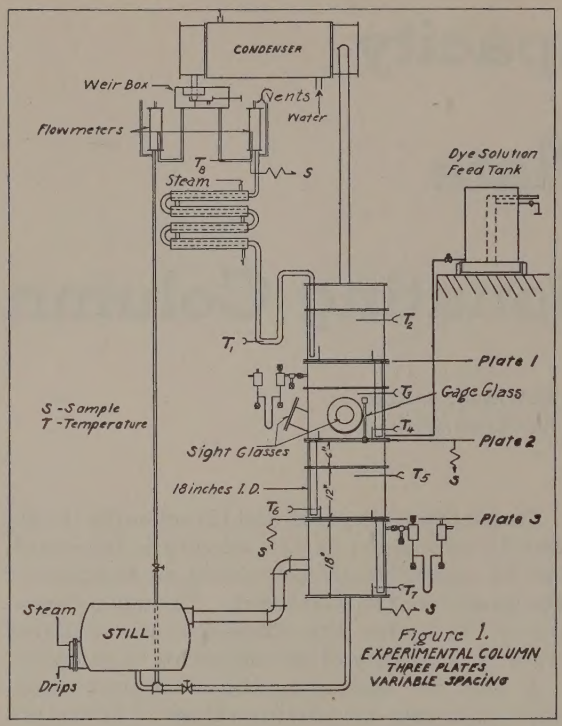


Figure 1. EXPERIMENTAL COLUMN THREE PLATES VARIABLE SPACING

Experimental data are needed for entrainment during actual distillation. Further, it is felt that there is a need for a set of experimental data which will show, for vapor rates high enough to be of practical interest, the effect on the plate efficiency of such variables as depth of liquid on the plate, plate spacing, and reflux ratio.

The work presented here represents an effort to supply such a set of experimental data.

Description of Apparatus

In designing the distilling column care was taken to provide sufficient heating and condensing surface to permit the column to be run at high vapor velocities.

The size of the column was made as large as the available heating surface would permit. The inside diameter was 18 inches; each plate contained ten bubble caps. Data from a column of this size should be directly applicable, in a great many cases, to the design of industrial columns.

Although only one plate was to be studied, the column was built with three plates. In this way conditions in an actual column were simulated as closely as possible by placing a plate above and a plate below the one under study.

The distillation apparatus is shown diagrammatically in Figure 1:

The still was of 250 gallons capacity and was heated by a closed steam coil. The vapors passed upward through the three-plate column into a tubular condenser where they were totally condensed. The condensate then passed through a weir box. The latter consisted of a rectangular box which moved in front of a straight weir such that the condensate could be divided into two streams, reflux and product.

Each stream passed through a separate flowmeter where it was measured. The reflux was returned through a steam heater to the top of the column. The product was returned direct to the still to keep the liquid in it at a constant composition.

The column proper was made up of flanged sections with an inside diameter of 18 inches. By changing the positions of the flanged sections, plate spacings of 6, 12, and 18 inches could be obtained. When a section was taken from between two plates, it was placed above the top plate. In this way the over-all height of the column was kept the same.

In the 12-inch flanged section above the center plate there were two 4-inch Pyrex sight glasses 90° apart, through which it was possible to observe the bubbling action on the center plate. For a plate spacing of 6 inches the special section was placed so as to permit observation of the top plate.

The column was insulated by means of two 1-inch layers of wool felt held in place by iron bands. The vapor lines were insulated by means of 1-inch asbestos pipe covering. U-tube manometers were placed so as to measure the pressure drop across the center and bottom plates. Thermocouples were placed in the vapor space above each plate and in the liquid entering each plate.

The bubble plates themselves were of standard alternate down-pipe construction. The details of the plates are given in Figure 2.

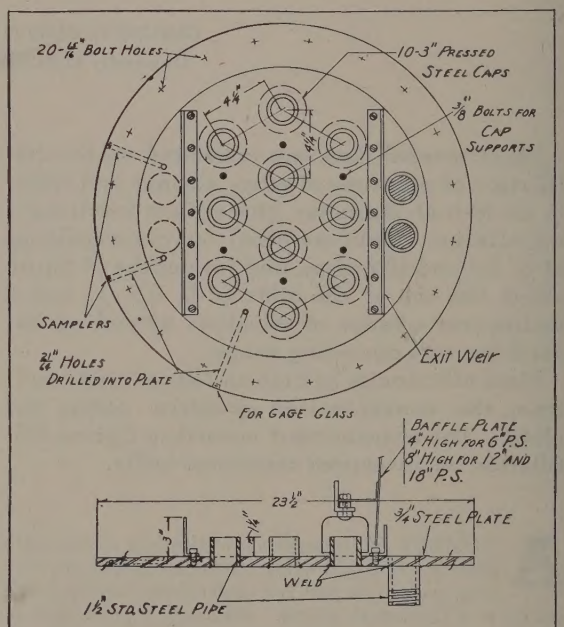

20-11/16" Bolt Holes
10-3" Pressed Steel Caps
3/8" Bolts for Cap Supports
Samplers
21/64" Holes Drilled into Plate
Exit Weir
For Gage Glass
Baffle Plate 4" High for 6" P.S. 8" High for 12" and 18" P.S.
3/4" Steel Plate
Weld
1 1/2" Sta. Steel Pipe

FIG. 2A PLATE LAY-OUT

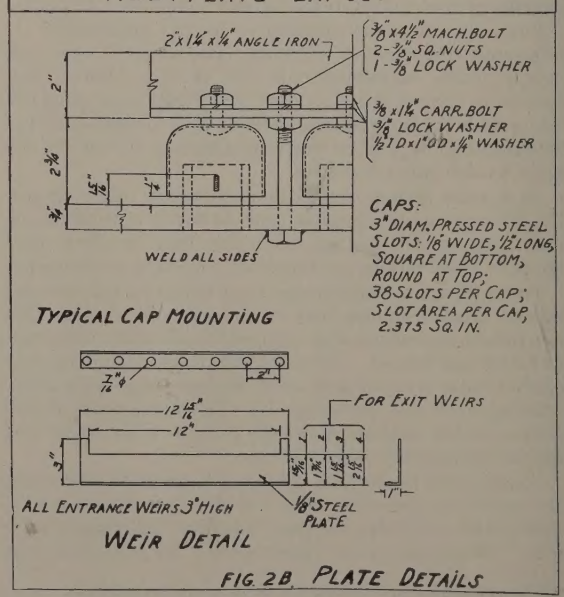

2"x1 1/4"x1/4" Angle Iron
3/8"x4 1/2" Mach. Bolt
2-3/8" Sq. Nuts
1-3/8" Lock Washer
3/8"x1 1/4" Carr. Bolt
3/8" Lock Washer
1 1/2" D x 1" OD x 1/4" Washer
Weld All Sides
CAPS:
3" Diam. Pressed Steel
Slots: 1/16" Wide, 1/2" Long, Square at Bottom, Round at Top;
38 Slots per Cap;
Slot Area per Cap, 2.375 Sq. In.
Typical Cap Mounting
For Exit Weirs
All Entrance Weirs 3" High
1/8" Steel Plate
Weir Detail

FIG. 2B. PLATE DETAILS

The liquid entered a plate at the side and flowed directly across and out over a straight weir 12 inches long. These weirs were removable, so that by substituting weirs of different heights the liquid level on a plate could be varied. The weirs were screwed to the plate by means of cap screws and made tight by sealing with shreds of asbestos rope which had been soaked in a mixture of litharge and glycerol. Each plate contained ten 3-inch pressed steel caps. Slots in the caps were $^1/_2$ inch high and $^1/_8$ inch wide, square at the bottom, and round at the top, with thirty-eight slots per cap. The slot area per cap was 2.375 square inches. The total slot area per plate was 23.75 square inches, or 9.35 per cent of the free area of the column.

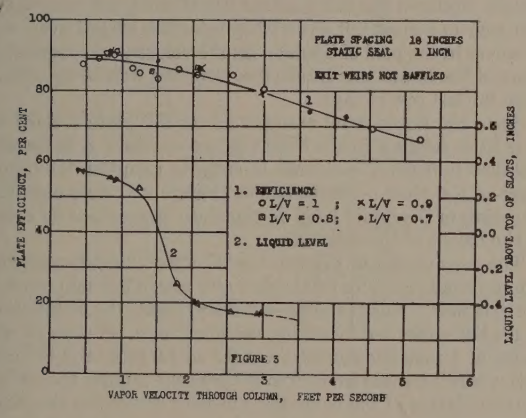


PLATE SPACING 18 INCHES
STATIC SEAL 1 INCH
EXIT WEIRS NOT BAFFLED
1. EFFICIENCY
○ L/V = 1 ; × L/V = 0.9
□ L/V = 0.8; • L/V = 0.7
2. LIQUID LEVEL
PLATE EFFICIENCY, PER CENT
LIQUID LEVEL ABOVE TOP OF SLOTS, INCHES
VAPOR VELOCITY THROUGH COLUMN, FEET PER SECOND
FIGURE 3

Liquid samples were withdrawn from behind the entering weir on each plate. This meant that the sample for any particular plate was taken at the point where it entered the plate below. This was done since the sample could be more easily withdrawn from the large pool of liquid maintained behind the entering weir. To determine whether the sample taken in this manner was contaminated by the liquid splashing over the entering weir from the plate, several runs were made in which samples were taken of the liquid as it left the top plate and where it entered the center plate. No appreciable difference in composition could be found. On the center plate a gage glass was attached to a drilled connection into the cap area in order to observe the actual liquid level existing on the plate while running.

For all except a preliminary set of runs a baffle was placed in front of the exit weir on each plate, as shown in Figure 2, in order to prevent the liquid from surging over the weirs as a result of the wave motion in the liquid and the splashing over as a result of the weir being located quite close to the last row of caps. These baffles were 8 inches high for the runs at 18- and 12-inch plate spacings, and 4 inches high for the runs at 6-inch plate spacing. On the center plate this baffle was of glass so as not to interfere with the observation of the action on the center plate.

Procedure

All entrainment runs were made while running the column under total reflux. In making determinations of entrainment in the column, a dye solution was fed behind the entering weir on the center plate. This made it necessary in making entrainment runs to take the sample for the top plate from in front of the leaving weir on the top plate rather than from behind the entering weir on the center plate, as was ordinarily done. Samples were taken of the distillate and from the center and top plates, the concentration of dye was estimated from the color determined by means of a colorimeter which utilized a photoelectric cell, and the entrainment was calculated as follows:

$$e_1 = \frac{C_d}{C_1 - C_d}; \quad e_2 = \frac{C_1}{C_2 - C_1}$$

The usual balances in calculating the quantity of entrainment are given by Holbrook and Baker (*5*) or Sherwood and Jenny (*10*).

Determinations of plate efficiency were not made for the runs in which dye solution was fed into the column since it was felt that the presence of the dye might cause some error in the results.

Liquid samples were taken from the plates and from the distillate for plate efficiency determinations. Vapor samples were not taken because of the difficulty of obtaining a representative vapor sample. However, for a column running under total reflux, as was the case in most of the runs, the composition of the liquid leaving a plate is identical with the composition of the vapor entering the plate, so that analysis of the liquid sample gave at the same time the composition of liquid leaving one plate and average composition of vapor rising from the plate below. For those few runs made at reflux ratio (L/V) other than 1, the vapor compositions were calculated by the usual material balances.

The efficiencies for the center plate were evaluated using the definition of plate efficiency as given by Murphree (*7*).

$$E = \frac{Y_n - Y_{n-1}}{y^*_n - Y_{n-1}} \qquad (1)$$

In making a set of runs, steam was admitted to the coils in the still, and the column was given several hours in which to come to a steady state. When conditions in the column had become constant, as indicated by the constant reading of the flowmeter and constant temperatures throughout, samples of the distillate and from each plate were withdrawn continuously over a period of 15 to 20 minutes. During this time several sets of temperature and pressure readings were recorded. After these samples had been taken, the steam to the heating coils was readjusted to give a different vapor rate, and about an hour was allowed to elapse to permit the column to become steady at the new set of conditions. These changes of heat input to the still were usually made in rather small increments so that the column would again quickly reach a steady state.

Vapor velocities through the column were calculated from the flowmeter readings. The velocities recorded are those existing in the vapor space above the center plate (plate 2), which was the one studied. Since the reflux was returned to the top of the column slightly below its boiling point, some vapor leaving the center plate was condensed on the top plate. The amount of vapor from plate 2 so condensed was calculated for each run, and this amount was added to the flowmeter readings in order to arrive at the moles of vapor leaving the center plate.

The system ethyl alcohol-water was chosen for this work because of its commercial importance and because physical data on this system have been thoroughly worked out.[2] The vapor-liquid equilibrium data for alcohol and water used are those of Carey (*2*). He made very careful determinations, and his data have been subsequently checked closely by Cornell and Montonna (*4*).

In determining plate efficiencies for this work, Carey's equilibrium data were replotted on a large scale, using a fictitious molecular weight for water of 16.8 instead of 18 in order to correct for the inequality of the latent heats of alcohol and water.

Effect of Variables on Plate Efficiency

The experimental data are shown graphically in Figures 3 through 17. The first set of runs makes up Figure 3. In this series the plate spacing was 18 inches and the static seal 1 inch. The term "static seal" is used to designate the apparent liquid level above the top of the slots with no crest above

[2] The percentage of alcohol in a mixture can be determined with sufficient accuracy by means of specific gravity. The specific gravity of the alcohol-water mixtures was determined by mean sof a specific gravity balance of the Chainomatic type.

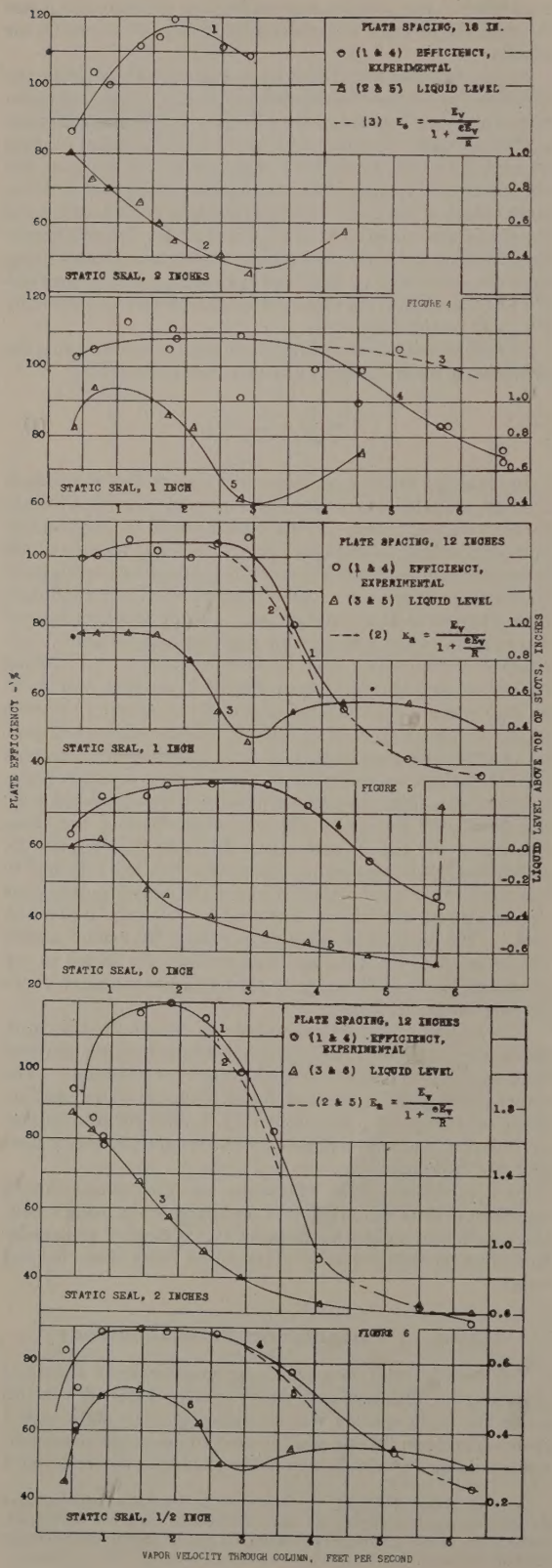


PLATE SPACING, 18 IN.
○ (1 & 4) EFFICIENCY, EXPERIMENTAL
△ (2 & 5) LIQUID LEVEL
-- (3) $E_o = \frac{E_V}{1 + \frac{cE_V}{R}}$
STATIC SEAL, 2 INCHES
FIGURE 4
STATIC SEAL, 1 INCH
PLATE SPACING, 12 INCHES
○ (1 & 4) EFFICIENCY, EXPERIMENTAL
△ (3 & 5) LIQUID LEVEL
--- (2) $E_a = \frac{E_V}{1 + \frac{cE_V}{R}}$
STATIC SEAL, 1 INCH
FIGURE 5
STATIC SEAL, 0 INCH
PLATE SPACING, 12 INCHES
○ (1 & 4) EFFICIENCY, EXPERIMENTAL
△ (3 & 6) LIQUID LEVEL
--- (2 & 5) $E_a = \frac{E_V}{1 + \frac{cE_V}{R}}$
STATIC SEAL, 2 INCHES
FIGURE 6
STATIC SEAL, 1/2 INCH
PLATE EFFICIENCY - %
LIQUID LEVEL ABOVE TOP OF SLOTS, INCHES
VAPOR VELOCITY THROUGH COLUMN, FEET PER SECOND

the exit weir. Numerically it is the height of the exit weir above the top of the slots.

In these runs the L/V ratio was varied from 0.7 to 1.0. There is no measurable change in efficiency for this variation of L/V ratio.

Figure 3 shows that the efficiency decreased continuously as the velocity was increased, and also that the liquid level fell off rapidly. The gage glass readings show that the liquid level, even at low vapor rates, was considerably below the level of the exit weir. Visual observation through the sight glasses disclosed the fact that the liquid did not flow over the exit weir in a crest but at very low velocities surged over, due to waves in the pool of liquid. As the velocity was increased, more of the liquid was transferred over the weir by splashing from the last row of caps.

Since the liquid level maintained on the plate seemed to bear little relation to the height of the exit weir, a baffle was installed in front of each weir in order to maintain the liquid level on the plate. These baffles (Figure 2*A*) were essential to maintain the liquid level on the plate approximately equal to the height of the exit weir.

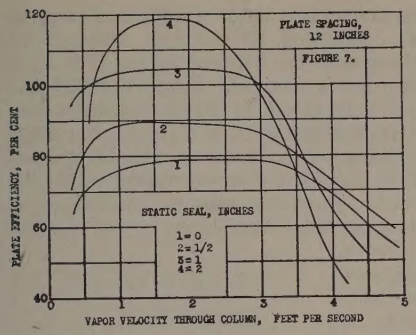
The runs shown in Figures 4 to 17 were all made with the column running under total reflux and with a baffle in front of the exit weir. For the same exit weir height, the installation of the baffle resulted in raising the liquid seal, at a vapor velocity of 1 foot per second, from 0.3 to 1.0 inch, and the efficiency was increased from 89 to 107 per cent (Figure 4). After the installation of the baffle the bubbling action on the plate was also altered. The liquid on the plate was churned into a fine froth or foam which increased in depth as the velocity increased, whereas before installing the baffle a great deal of coarse spray was formed, even at low velocities.

These results emphasize the fact that care must be taken in the design of a bubble plate if the actual liquid level maintained on the plate is to be equal to or greater than the leaving weir or downpipe. The leaving weir or downpipe should be located sufficiently far from the last row of caps to provide a quieting area, or some sort of baffling, such as is used here, should be provided. In these runs the gage glass reading of the liquid level usually attained a value equal to the height of the exit weir at a velocity of 1 to 1.5 feet per second, and then fell off rather rapidly, finally tending towards a constant value as the velocity increased. There is some question as to the significance of these gage glass readings. The connection to which the gage glass was attached opened into the turbulent region among the caps, and the decrease in the reading of the gage glass may be due in some part to vapor lift action on the plate. On a large bubble-cap plate on which air was being bubbled through water, it has subsequently been observed that the gage glass connected in the turbulent cap area registered considerably lower liquid level values than the gage glass attached to the quiet pool of liquid surrounding the downflow pipe.

In Figure 12 plate efficiencies are plotted against the mole per cent of alcohol in the liquid leaving the center plate. Over the concentration ranges covered there seems to be no difference in the plate efficiency. Carey et al. (*1*) likewise found for the mixture benzene-toluene that the efficiency was independent of the concentration over a wide range, although there was some deviation from this for mixtures with small concentrations of either component.

The pressure drop data are shown in Figure 13 in which the pressure drop across two plates in millimeters of mercury is plotted against vapor velocity through the column in feet per second.

At 12-inch plate spacings runs were made with liquid static seals of 0, $^1/_2$, 1, and 2 inches. For comparison, this family of curves is plotted together as Figure 7. In all cases the efficiency rose rather rapidly, remained constant over a con-



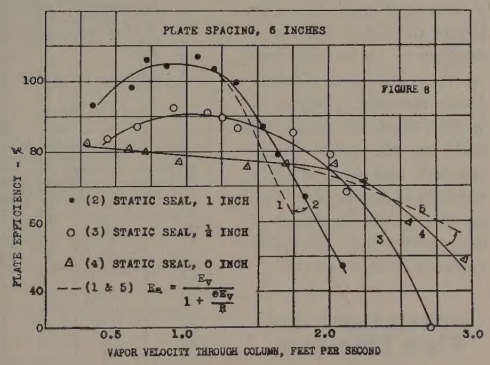


PLATE SPACING, 6 INCHES
FIGURE 8
• (2) STATIC SEAL, 1 INCH
○ (3) STATIC SEAL, ½ INCH
△ (4) STATIC SEAL, 0 INCH
PLATE EFFICIENCY - %
VAPOR VELOCITY THROUGH COLUMN, FEET PER SECOND

siderable range,[3] and then began to decrease, as the velocity was increased from a low to a high value. The efficiencies at very low vapor rates tend to scatter considerably, particularly for the higher liquid depths. This is apparently due to the fact that for low velocities wave motion in the pool of liquid on the plate results in a spasmodic type of bubbling. As the velocity is increased, the bubbling becomes more uniform and the liquid is whipped into a fine froth. As the velocity is further increased, the depth of the froth layer increases and may attain a depth of 4 to 6 inches. As the vapor velocity is increased still further, the liquid can be seen to be "coned" back from the caps. Large slugs of liquid are thrown outward, and again bubbling in the plate surges unevenly.

A portion of some of the curves at high velocities is shown as dotted lines because in this region the liquid has begun to pile up on the plates and the column is really being operated beyond its safe limit. It cannot be determined accurately where flooding begins for any particular setting of plate spacing and weir height since the flooding point will vary considerably with the speed with which the vapor velocity is increased. That is, if the heat input to the still is increased too rapidly, the column will flood more quickly than if the velocity is brought up slowly. For this reason a column must always be operated considerably below the velocity that would cause flooding.

As the liquid level on the plate is increased, the allowable velocity through the column is decreased (Figure 7). As the plate spacing is decreased, the allowable velocity is decreased. Any generalization as to the allowable vapor rate through the column, then, should take into account not only plate spacing but also depth of liquid on the plate.

The plate efficiencies, ranging up to 120 per cent, obtained with the column were surprisingly high inasmuch as no such high values had been reported previously for alcohol-water mixtures.

As pointed out by Peters (*9*), when a concentration gradient across the plate exists, values of the over-all Murphree plate efficiency of greater than 100 per cent can be obtained. Figure 14 shows the results from four runs in which the composition of the liquid was measured at several points on the plate. The concentration varies almost linearly from the entering to the leaving composition. If at any particular point on the plate a value for the efficiency is assumed (called the "local efficiency" after Lewis, *6*), it is possible to draw a curve for the composition of the vapor rising from the liquid as it travels across the plate.

Such curves have been constructed in Figure 15 in which the mole per cent alcohol in the vapor rising from the liquid has been plotted against the fractional area of the column which has been traversed by the liquid. Obviously this factor will vary from 0 to 1 as the liquid flows across the plate. Using these curves, values for the average vapor composition for each run were obtained by integrating the curves in a graphical stepwise method, using an assumed value for the local efficiency at any point on the plate as 0.85. If we assume, as suggested by Lewis (*6*), that the vapors entering the plate are completely mixed, we can then obtain a value of the over-all Murphree efficiency from the equation:

$$E = \frac{(Y_n)_{av.} - Y_{n-1}}{y^*_n - Y_{n-1}} \qquad (2)$$

The values of the over-all efficiency based on these calculated values of $(Y_n)_{av.}$ are shown in Figure 15. For the assumed local efficiency of 85 per cent, the calculated over-all efficiencies check the experimental values closely except in the case of run 42, which on other criteria also appears to give nonconcordant results.

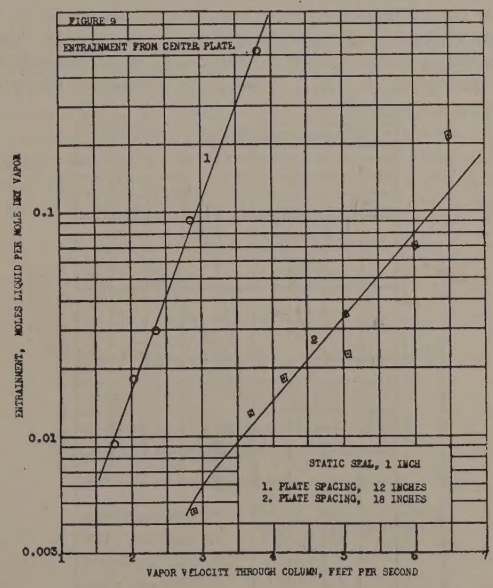


FIGURE 9
ENTRAINMENT FROM CENTER PLATE
STATIC SEAL, 1 INCH
1. PLATE SPACING, 12 INCHES
2. PLATE SPACING, 18 INCHES
ENTRAINMENT, MOLES LIQUID PER MOLE DRY VAPOR
VAPOR VELOCITY THROUGH COLUMN, FEET PER SECOND

Lewis (*6*) presented equations based on certain simplifying assumptions by means of which the over-all efficiency of a bubble plate may be calculated for various conditions of flow. As case 1, Lewis took an alternate downpipe plate, such as that used here. He assumed that the vapors entered the plate perfectly mixed and that the composition of the liquid on the plate varied linearly from entering to leaving composition; that is, he assumed that there was no mixing of the liquid.

[3] As explained by Carey et al. (*1*), it would be expected that the efficiency would increase as the velocity was increased for low velocities; on a given plate increasing the vapor rate tends to increase the time of contact since some of the bubbles escape at a lower level as the slot opening increases and so must travel upward through a greater depth of liquid.

The equilibrium line was assumed to be straight over the range considered. Lewis' equation for case 1 is:

$$E_0 = \frac{e^{E_L\lambda} - 1}{\lambda} \qquad (3)$$

$\lambda = K/R$ where $R = L/V$
K = slope of equilibrium line, or dy^*/dx
e = base of Naperian logarithm system

For comparison, values of E_0 were calculated for the four runs shown in Figure 15 and are shown as Table I. For an assumed local efficiency of 90 per cent the values of E_0 check the experimental values, except in the case of run 42 as above.

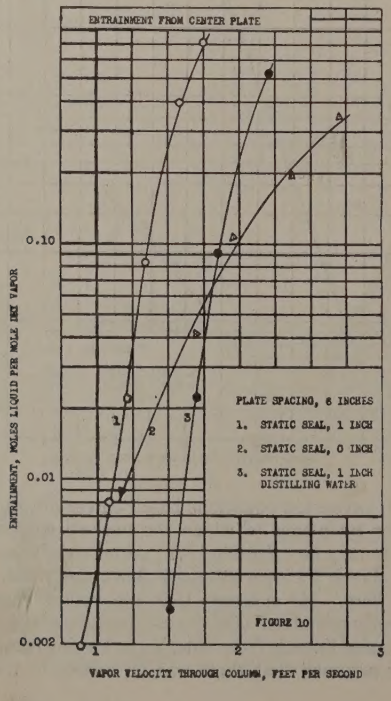
It appears, then, that for an over-all efficiency for the plate used in this work of about 110 per cent the actual vapor-liquid efficiency is 85 to 90 per cent.

TABLE I. OVER-ALL EFFICIENCY CALCULATED FROM CASE 1 (6)

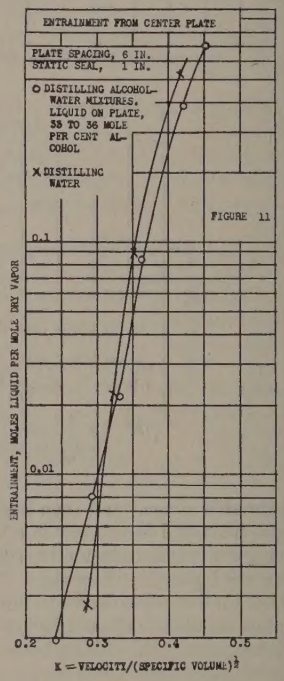
Run No.	Experimental Efficiency	$E_0 = \left(\frac{e^{E_L\lambda} - 1}{\lambda}\right)$ E = 0.87[a]	E = 0.90[a]	E = 0.95[a]
	%	%	%	%
41	108	105	109	116
42	91	108	113	121
46	113	106	110	118
47	111	105	109	117

[a] Assumed values.

According to Murphree's derivation (7), when log $(1 - E)$ is plotted against liquid depth at least for low velocities, a straight line should result. Carey (2) found this to be true except at very low liquid depths where the curve deviated from a straight line. Using the data for 12-inch plate spacing (Figure 7), the plot of Figure 17 was made. The efficiency values at moderate velocities on the flat portions of the curve were taken as the dry vapor efficiencies. Since values of E greater than 1 give a value of $(1 - E)$ which is negative, the efficiency for each seal was corrected to give a value less than 1 by dividing by the value $E_{max.}$, arrived at from the calculations of Figure 15. $E_{max.}$ means the maximum efficiency that may be expected from this plate. On Figure 17 a curve was drawn for $E_{max.}$ values of 1.3 and 1.4. Although the slope of the line changes for the different values of $E_{max.}$, in both cases a straight line is obtained. Carey (2) found that the slopes of the lines for log $(1 - E)$ *vs.* depth of immersion were about the same for slot widths of $^1/_2$ to $^1/_8$ inch. For a slot width of $^1/_{16}$ inch the slope of the line is considerably greater. Slots widths used in practice are almost always within the limits of $^1/_8$ to $^1/_2$ inch. For most cases, then, the efficiency at various seals can be predicted if the efficiency for two values of the liquid depth is known.



For a plate spacing of 6 inches, runs were made at a static seal of 0, $^1/_2$, and 1 inch. These are shown as Figure 8. The shape of these curves is similar to those obtained for the runs at a 12-inch plate spacing. Again it is seen that, as the liquid level on the plate is increased, the allowable velocity is decreased; and as the plate spacing is decreased, the allowable velocity is decreased.



Entrainment and Plate Efficiency

Entrainment was determined for plate spacings of 18 and 12 inches at 1-inch seal (Figure 9), and for a plate spacing of 6 inches at a seal of 1 and of 0 inch, as well as a series with a static seal of 1 inch when distilling pure water (Figure 10).

The series of runs when distilling water was made in order to estimate the difference in entrainment for two materials run in the same apparatus. These entrainment data for water and for alcohol-water at 6-inch plate spacing were plotted in several ways and are given in Table II. The best correlation was obtained when the entrainment was plotted against $K = u / \left(\frac{1}{d_2}\right)^{1/2}$, as shown in Figure 11. The empirical equation

$$u = K \left(\frac{1}{d_2}\right)^{1/2} \qquad (4)$$

has been used with good results in correlating allowable velocities and appears to offer promise as a means of correlating entrainment data for materials not too dissimilar in nature.

In Figure 18 entrainment data from several sources have been plotted versus $K = u / \left(\frac{1}{d_2}\right)^{1/2}$. At 18-inch plate spacing the authors' data check fairly well with those of Strang (12) on air and water at the higher velocities. The data of Sherwood and Jenny (10) do not extend into the higher range. At a 12-inch plate spacing the authors' data on alcohol-water are higher than those of the other investigators.

The divergence of the various sets of data are not surprising in view of the considerable differences in type and arrangement of caps, depth of liquid on the plate, and other conditions. More data are needed on the distillation of different systems

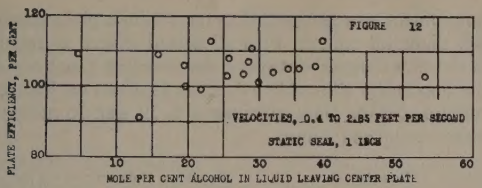
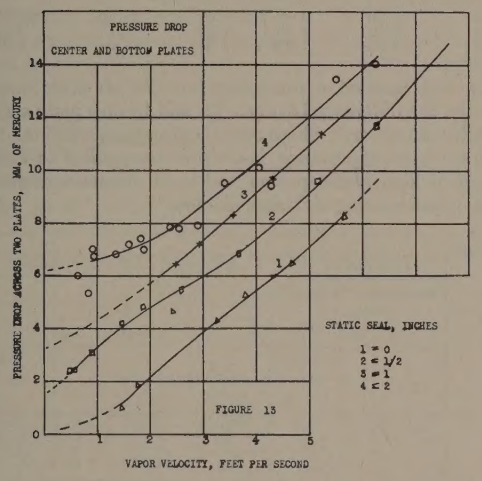
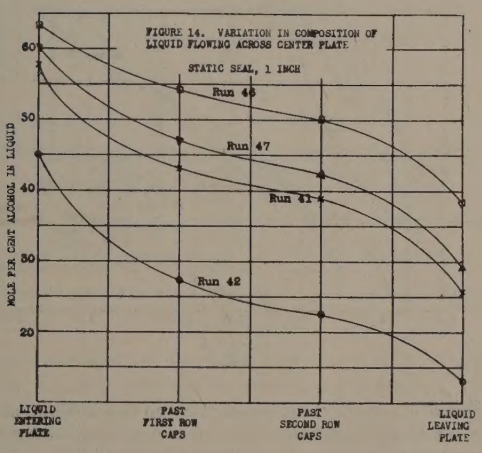


FIGURE 12
VELOCITIES, 0.4 TO 2.85 FEET PER SECOND
STATIC SEAL, 1 INCH
PLATE EFFICIENCY, PER CENT
MOLE PER CENT ALCOHOL IN LIQUID LEAVING CENTER PLATE





in the same apparatus before any conclusion can be drawn as to the best means of correlating entrainment data.

With these data it is possible to determine whether or not the observed entrainment is sufficient to account for the total loss in efficiency. The dotted curves of Figures 4, 5, 6, and 8 represent the efficiency curves that would be predicted on the basis of entrainment.

In calculating these curves the simplified equation of Colburn (*3*) was used; for the case of total reflux it is:

$$E_a = \frac{E_v}{1 + e(E_v)} \qquad (5)$$

From the experimental curves the value for E_v was taken to be that at moderate velocity on the flat portion of the efficiency *vs.* velocity curve.

The more rigorous equation of Colburn gives results differing by less than 8 per cent from those obtained from the simplified equation.

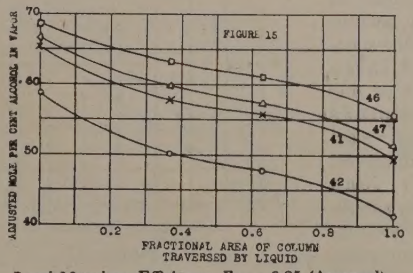
TABLE II. CORRELATION OF ENTRAINMENT DATA AT A PLATE SPACING OF 6 INCHES AND A LIQUID SEAL OF 1 INCH

e, Entrainment	Velocity, u	W	Vapor Density, d_2	$1/d_2$	Liquid Density, d_1	$K = \frac{u}{(\frac{1}{d_2})^{1/2}}$
	Ft./sec.	*Lb./hr./sq. ft.*	*Lb./cu. ft.*		*Lb./cu. ft.*	
			Distilling Alcohol-Water			
0.00195	0.88	240	0.0758	13.20	51.0	0.242
0.00800	1.08	292	0.0752	13.30	50.5	0.296
0.02200	1.21	326	0.0752	13.30	51.0	0.331
0.08400	1.34	354	0.0735	13.60	51.0	0.363
0.39000	1.58	404	0.0710	14.10	51.0	0.421
0.71000	1.75	420	0.0669	14.95	51.1	0.451
			Distilling Water			
0.00280	1.51	201	0.0360	27.80	59.8	0.286
0.02250	1.70	226	0.0360	27.80	59.8	0.323
0.09100	1.85	247	0.0360	27.80	59.8	0.351
0.53000	2.21	295	0.0360	27.80	59.8	0.417

Figure 4 shows that the efficiency, as calculated from the observed entrainment for 18-inch plate spacing and 1-inch seal, is considerably greater than the observed plate efficiency. This would indicate that for velocities beyond 4.5 feet per second there is some reduction in efficiency over and above that due to the entrainment of liquid from plate to plate. In observing the action on the plate for velocities in the neighborhood of 4.5 to 6 feet per second, it could be seen that the velocity of the vapor emerging from the slots was high enough to "cone" the liquid back from the cap considerably. This should result in poorer contacting of liquid and vapor with a resultant loss in efficiency. For a column with a slot area equivalent to 15 per cent of the free area of the column, instead of 10 per cent as in this case, it is probable that the reduction in slot velocities would result in bringing the observed efficiency curve closer to the values calculated from the entrainment.

For the lower plate spacing the values of E_a, as calculated, agree satisfactorily with the observed plate efficiencies.

Sherwood and Jenny (*10*) found that the quantity of entrainment for the system air-water was approximately proportional to the depth of liquid on the plate; that is, when the liquid depth above the top of the slots was doubled, the entrainment was approximately doubled. Using this relationship, it was assumed that the entrainment for a 12-inch plate spacing and a 2-inch seal was double that observed for a 1-inch seal, and that the entrainment for the same spacing with a seal of



Local Murphree Efficiency, E_L = 0.85 (Assumed)

Run No.	$(Y_n)_{av.}$	Over-all Efficiency Based on $(Y_n)_{av.}$	Over-all Efficiency Exptl. $(Y_n = X_{n+1})$
41	57.1	111%	108%
42	49.2	108	91
46	62.2	115	113
47	58.8	113	111

1/2 inch was half that at a seal of 1 inch. Using these predicted values for entrainment at a 2-inch and a 1/2-inch seal, the dotted curves 2 and 5 in Figure 6 were calculated by Colburn's equation as in the previous cases. These two calculated curves likewise agree with the experimental curve.

The foregoing shows that, if the dry plate efficiency, or

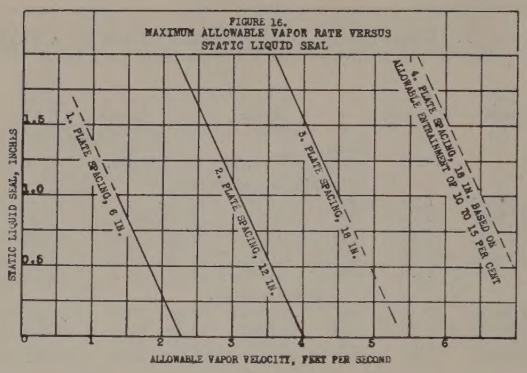


FIGURE 16.
MAXIMUM ALLOWABLE VAPOR RATE VERSUS
STATIC LIQUID SEAL
1. PLATE SPACING, 6 IN.
2. PLATE SPACING, 12 IN.
3. PLATE SPACING, 18 IN.
4. PLATE SPACING, 18 IN. BASED ON ALLOWABLE ENTRAINMENT OF 10 TO 15 PER CENT
STATIC LIQUID SEAL, INCHES
ALLOWABLE VAPOR VELOCITY, FEET PER SECOND

efficiency at velocities such that there is essentially no entrainment, is known for a given substance for two values of the liquid depth and if the variation of entrainment with velocity at a particular liquid depth and plate spacing is known, a family of curves for that plate spacing (Figure 7) can be predicted to a fair degree of approximation for moderate plate spacings.

Allowable Vapor Velocity

A curve of considerable practical value is shown in Figure 16. The depth of liquid seal was plotted against the maximum allowable vapor rate for lines of constant plate spacing. For 6-inch and 12-inch plate spacings the maximum allowable velocities correspond to 10–15 per cent entrainment. Dotted curve 4 represents the allowable velocity that would be predicted for an 18-inch plate spacing on the basis of 10 per cent entrainment. This is considerably higher than the actual capacity determined by the point at which the efficiency begins to decrease. In each case for any particular liquid seal and plate spacing the maximum allowable velocity is taken to be at that point at which the efficiencies begin to decrease markedly. For a conservative design figure 80 per cent of these values could be taken.

The data from Figure 16 make it possible to calculate whether it is cheaper to build a column of low plate spacing and large diameter or one of high plate spacing and small diameter. Rather than make any simplifying assumptions concerning the variation of cost with height and cross-sectional area, it is felt that such calculations would be of much more value if based on actual estimates of column cost. Detailed estimates of the cost of five different columns, such as might be used for alcohol distillation, were obtained from the Estimating Department of E. B. Badger and Sons Company. Over a limited range it was possible to plot the cost of the column against plate spacing and also against column area. These cost figures follow:

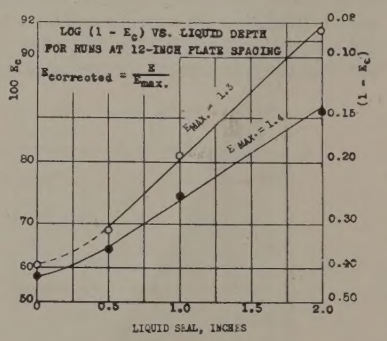


FIGURE 17

Plate spacing, in.	7	11	11	15	11
Column diam., in.	42	42	18	42	44
No. of plates	20	20	20	20	20
Cost	$1106	$1245	$397	$1310	$1341

The problem was assumed that for a 6-inch plate spacing a 42-inch diameter column with 20 actual plates is required. Using the experimental data for a static seal of 1 inch and taking the maximum allowable velocities as given on Figure 16, the column cost for plate spacings of 6, 12, and 18 inches was calculated to be as follows:

Plate Spacing	Allowable Velocity	Efficiency	No. of Plates	Column Diam.	Cost of Column
In.	*Ft./sec.*			*In.*	
6	1.35	0.98	20	42.00	$1095
12	3.10	0.98	20	27.75	645
18	4.50	0.98	20	23.00	680

The cost reached a minimum for 12-inch plate spacing although the difference between 12- and 18-inch plate spacing is small. In general, where other considerations such as head room are of no importance, it is more economical to build a column of high plate spacing and small diameter than one of low plate spacing and large diameter.

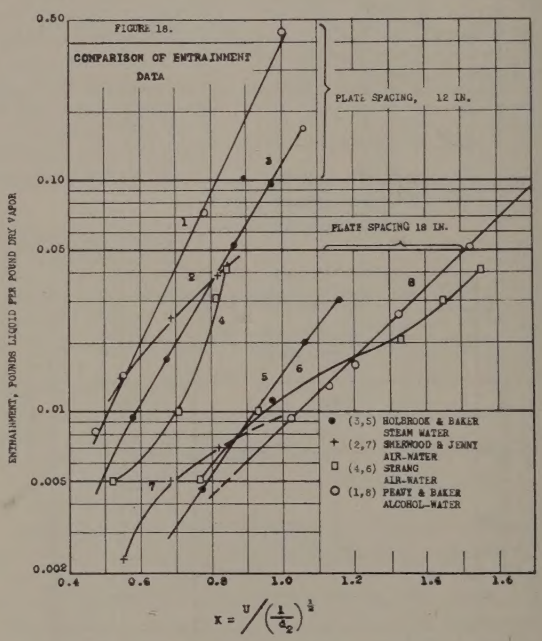


FIGURE 18.
COMPARISON OF ENTRAINMENT DATA
PLATE SPACING, 12 IN.
PLATE SPACING 18 IN.
ENTRAINMENT, POUNDS LIQUID PER POUND DRY VAPOR
(3,5) HOLBROOK & BAKER STEAM-WATER
(2,7) SHERWOOD & JENNY AIR-WATER
(4,6) STRANG AIR-WATER
(1,8) PEAVY & BAKER ALCOHOL-WATER
X = U / (1/d_2)^1/2

Colburn (*3*) derived an expression for the amount of entrainment occurring when a column is operating at the economic velocity. "Economic velocity" means that point at which the increased number of plates required because of lower efficiency counterbalances the saving in the column cross-sectional area. Colburn assumes that entrainment data can be approximately represented by the equation:

$$e = au^n \qquad (6)$$

The cost of a column, c, is assumed to be proportional to the cross-sectional area, A, and the number of plates; the number of plates is equal to the number of theoretical plates, N, divided by the plate efficiency, E_a, or

$$c = ba\frac{N}{E_a}, \text{ and } A = \frac{V}{u} \qquad (7)$$

where a and b are constants

The rate of cost change with entrainment is found, and, solving for the entrainment at minimum cost, Colburn obtains:

$$e_{\text{optimum}} = \frac{R}{(n-1)E_a} \qquad (8)$$

Optimum velocities were calculated from the experimental data obtained in this work, using the observed values of plate efficiencies and Colburn's equation for cost:

$$c = bAN\frac{1}{E_a};\ A = \frac{V}{u}$$

In order to determine the values of n, the experimental entrainment data were plotted as ($\log e \times 100$) *vs.* $\log u$. Each set of data could be represented fairly well by a straight line, the slope of which was taken as n.

The results of these calculations are given in Table III. The values for the economic velocity, as predicted by Colburn (*3*), are so high as to be beyond the safe operating limit of the column.

It is interesting to note, however, that the values for the economic velocity, as calculated from the observed values of the efficiency, check those calculated from entrainment data by the use of Colburn's equation.

TABLE III. CALCULATION OF ECONOMIC VELOCITIES[a]

u	A	E_a (Obsvd.)	c	Optimum Velocity	e at Optimum Velocity	Value of $e_{optimum} = \frac{R}{(n-1)(E_v)}$
Ft./sec.	*Sq. ft.*			*Ft./sec.*		
			18-Inch Plate Spacing, 1-Inch Seal[b]			
1.0	10.00	1.080	$2780	...	...	...
2.0	5.00	1.080	1110	...	...	...
4.0	2.50	1.010	802	...	...	...
5.0	2.00	0.900	666	...	...	...
6.0	1.67	0.770	650	...	...	...
6.5	1.54	0.730	633	...	...	...
			12-Inch Plate Spacing, 1-Inch Seal			
1.00	10.00	1.040	2885	...	...	...
3.00	3.33	1.000	1000	...	...	...
3.33	3.00	0.920	978	3.33	0.220	0.213
3.40	2.94	0.880	1002	...	...	...
3.50	2.86	0.845	1014	...	...	...
			6-Inch Plate Spacing, 1-Inch Seal			
1.0	10.00	1.050	2857	...	...	...
1.5	6.67	0.890	2247	1.50	0.175	0.150
1.6	6.25	0.825	2775	...	...	...
1.7	5.88	0.760	2320	...	...	...
			6-Inch Plate Spacing, 0-Inch Seal			
1.0	10.00	0.790	3800	...	...	...
2.0	5.00	0.760	1975	...	...	...
2.5	4.00	0.640	1875	2.50	0.270	0.420
2.6	3.85	0.610	1895	...	...	...

[a] $c = bAN(1/E_a)$; assume $b = 15$, $A = V/u$, $V = 10$, $N = 20$.
[b] No minimum within the experimental range.

Summary

The variation of the plate efficiency for several liquid depths on the plate has been shown throughout a range of vapor velocities extending beyond the safe operating limit of the fractionating column. Starting at low velocities, as the vapor velocity is increased, the efficiency rises for a time, remains essentially constant over a considerable range, and then begins to drop. As the plate spacing is increased, the allowable vapor rate through the column is increased; as the depth of liquid on the plate is increased, the allowable vapor rate through the column is decreased.

Within the limits of 0.7 to 1.0 the L/V ratio has no effect upon the plate efficiency.

It has been demonstrated that the values of the Murphree plate efficiency of over 100 per cent found in this work result from the concentration gradient in the liquid flowing across the plate.

The importance of designing a bubble plate so as to maintain the liquid level on the plate has been emphasized.

Pressure drop data have been recorded for several depths of liquid on the plate.

Entrainment in a distilling column in actual operation has been recorded for three different plate spacings; it has been shown that the efficiency curves, as predicted on the basis of entrainment alone, check the experimental curves for plate spacings of 6 and 12 inches. For the plate spacing of 18 inches the efficiencies, as predicted on the basis of entrainment, are higher than the experimental efficiencies.

It was shown that for moderate plate spacings the curves for efficiency *vs.* velocity for various liquid depths at a particular plate spacing can be approximated by calculation, if the efficiency is known at two values of the liquid depth and if the variation of entrainment with velocity for that plate spacing is known.

A plot for evaluating the maximum allowable velocity in distilling columns has been presented. Using this plot for allowable velocity, it was shown to be more economical to build columns of 12- and 18-inch plate spacing and small diameter than those of 6-inch plate spacing and large diameter.

The calculation of economic velocities from the experimental values of the efficiency check those calculated on the basis of entrainment and shows that the economic velocity for a distilling column is too high to be of practical interest.

These results indicate that the prediction of allowable rates in a column on the basis of entrainment is justifiable, at least for low plate spacings. This lends considerable confidence to the use of such methods of calculation for distilling columns.

Nomenclature

e_1 = entrainment from top plate, lb. liquid/lb. dry vapor
e_2 = entrainment from center plate, lb. liquid/lb. dry vapor
C = dye concn., lb./lb. soln.
Subscripts d, 1, 2 = distillate, top plate, and center plate, respectively
L/V = ratio, moles liquid overflow to moles vapor up the column
Y_n = comp. of vapor leaving plate n
y^*_n = compn. of vapor in equilibrium with the liquid leaving plate n
$n-1$ = plate below plate n
$n+1$ = plate above n
E = Murphree plate efficiency defined by Equation 1
E_a = apparent efficiency used by Colburn (*3*), or efficiency when there is entrainment
E_v = Murphree efficiency, based on dry vapor compns., or efficiency when there is no entrainment
E_0 = over-all efficiency of plate in Equation 3, also by Equation 1
E_L = local vapor efficiency at any point on the plate
u = vapor velocity through main body of column, ft./sec.
W = weight velocity through main body of column, lb./hr./sq. ft.
d_1 = density of liquid, lb./cu. ft.
d_2 = density of vapor, lb./cu. ft.
N = no. of theoretical plates
c = cost of column
V = vapor flowing in unit time
R = rate of change in cost with entrainment

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